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Much data in the ocean is Lagrangian in nature. Its full use in ocean prediction could advance significantly the Navy’s ability to predict ocean conditions. The ultimate vision of this project has been the development of a data assimilation scheme that would afford a full naval predictive capacity in fixed ocean regions which can be comprehensively surveyed by Lagrangian measuring devices. This is based on the use of dynamical systems ideas that can generate strategies for deploying Lagrangian observational devices and their associated sensors. An effective Lagrangian data assimilation scheme coupled with an optimal deployment strategy can form the basis of an integrated prediction scheme for the ocean that can feed on both purely Lagrangian and mixed source data.

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An Operational Technology for Assimilating Lagrangian Data Based on Dynamical Systems Techniques

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LONG-TERM GOAL

Much data in the ocean is Lagrangian in nature. Its full use in ocean prediction could advance significantly the Navy's ability to predict ocean conditions. The ultimate vision of this project has been the development of a data assimilation scheme that would afford a full naval predictive capacity in fixed ocean regions which can be comprehensively surveyed by Lagrangian measuring devices. This is based on the use of dynamical systems ideas that can generate strategies for deploying Lagrangian observational devices and their associated sensors. An effective Lagrangian data assimilation scheme coupled with an optimal deployment strategy can form the basis of an integrated prediction scheme for the ocean that can feed on both purely Lagrangian and mixed source data.

OBJECTIVES

This project has laid the groundwork of an operational technology for assimilating Lagrangian data. This new Lagrangian data assimilation platform is expected to be particularly effective in ocean regions where coherent structures such as ocean eddies dominate the circulation. The focus has been on: 1) The extension of our Lagrangian data assimilation (LaDA) approach into a flexible platform, through which a variety of moving instrument measurements, which may not be viewed as purely Lagrangian in a conventional sense, can be integrated; 2) The design of observing systems that take full advantage of all moving instruments; 3) The formulation of automated algorithms for optimal deployment strategies of the moving instruments so as to maximize the information content of the observations; and 4) The incorporation of dynamical systems theory to enhance our predictive skill, in particular through deciphering coherent structures and tracer fields associated with them.

APPROACH

Our approach is to develop and use LaDA as the basis of an operational technology that accommodates the assimilation of data from a variety of measurements by any type of moving instruments including drifters, floats, and AUVs. Such a platform is being developed through a hierarchy of models. Fundamental issues are addressed using idealized model flows. Basic tests have been performed on intermediate model flows, the double-gyre, shallow-water model with various wind forcings, and progressing to the realistic general circulation model for operational application in the Gulf of Mexico. We investigate to what extent Lagrangian data can be used to aid in the estimation of the threedimensional flow evolution. We have improved the LaDA method to more effectively deal with the chaotic nature of the Lagrangian dynamics. We address the localization and inflation issues that will help simplify estimates of error covariance and we have developed a Lagrangian Ensemble Kalman Filter (EnKF). This is a joint project by the two co-PIs, K. Ide (UCLA) and C.K.R.T. Jones (UNC-CH). G. Vernieres (now at NASA-Goddard) was a postdoctoral fellow who worked on the LaDA platform in the context of the Gulf of Mexico. Amit Apte (now at TIFR-Bangalore) was an earlier postdoctoral fellow. Apte worked jointly with C.K.R.T. Jones (UNC-CH) and Andrew Stuart (University of Warwick, UK) on applying Langevin sampling techniques to Lagrangian data assimilation. The work also incorporated a collaboration with Amarjit Budiraja (UNC-CH) and Elaine Spiller (Marquette, formerly a postdoc at SAMSI) on the implementation of a particle filtering approach to LaDA.

WORK COMPLETED

Progress has been made in advancing Lagrangian data assimilation towards operational use. This has been achieved through a coordinated effort to test and adjust the LaDA scheme together with designs and tests of optimal deployment strategies. Due to the very nature of Lagrangian motion, the dynamics is usually chaotic, at least in many sub-regions, filter divergence can ensue in a manner that is a challenge to anticipate. The underlying cause is the nonlinearity in the system.

We have now shown the assimilation of Lagrangian data using our scheme to be surprisingly effective in capturing eddy motion in the Gulf of Mexico. We have developed and implemented a multi-layer reduced gravity model of the Gulf of Mexico (GOM.) This modeling setup has been shown to be the simplest representation of the GOM that simulates the shedding of eddies from the Loop Current, known as the key dynamic effect in the GOM. It is a first step toward a detailed representation of the physics of the GOM. The horizontal discretization uses a curvilinear grid. It has a horizontal resolution of about twelve km in the region of the loop current.

To achieve high computational efficiency, the LaDA method based on the Ensemble Kalman Filter (EnKF) was implemented on a 4160-processor Dell Linux cluster at the University of North Carolina at Chapel Hill. The effectiveness of LaDA was investigated through a series of identical twin experiments. Various different scenarios of drifter data were formulated and their efficacy compared.

To help us understand the shortcomings of the Kalman filter based methods, such as EnKF and EKF, as well as those of the variational methods like 4D-VAR, we have formulated the DA problem in a Bayesian framework. This leads us to the posterior distribution of the state given observations over a certain interval of time. Thus, the problem is stated as a smoother rather than a sequential filter. This is natural for Lagrangian data assimilation applications and also for hindcasting and reanalysis. In addition, the structure of the posterior distribution contains the information about the observations and hence it is of interest in many applications.

The direct use of particle filtering has been another advance this year. We have implemented a novel adaptation of the particle filter that is tailored to Lagrangian data assimilation.

RESULTS

A series of identical twin experiments have shown that LaDA works effectively using a realistic GOM system with a small number of drifter observations. We have now compared various data acquisition formats. These are: Lagrangian 2d, where only the horizontal position of the drifter is recorded; Lagrangian 3d, where readings are taken from isopycnal floats; and Eulerian where data is taken at a, judiciously chosen, fixed position. The experiment is to test whether these data acquisition, and associated assimilation, schemes can recover an eddy (detached from the Loop Current) that is missing from the model run. The initializations are shown in Figure 1 which show how the model run fails to capture the detaching eddy. The results are shown in Figure 2 and show a striking benefit from using LaDA 2d over the Eulerian scheme, and, in turn, LaDA 3d over LaDA 2d.

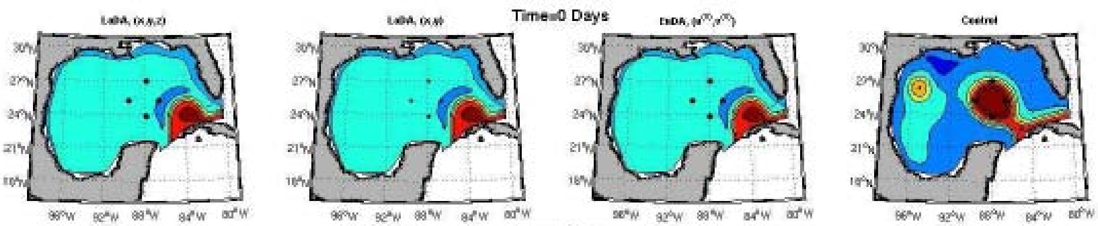

Figure 1.Colors represent the ssh field. The detaching eddy in the control run is absent from the initialization of the model run.

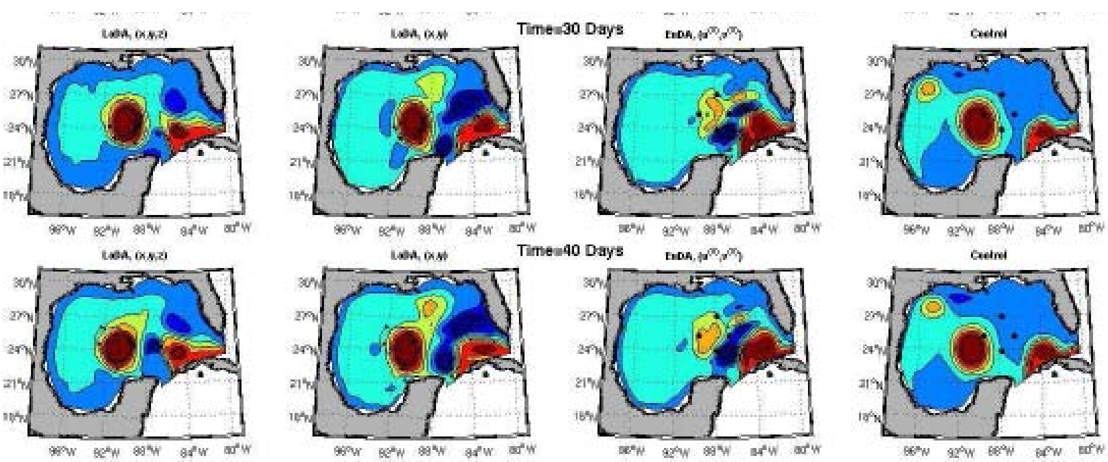

Figure 2. From left to right are the analyses, at 30 and 40 days from LaDA3d, LaDA2d and EuDA. These are to be compared with the control run on the right.

The remarkable efficiency of the methodology is investigated by looking at volumes of influence. We have defined these volumes as the regions that will be influenced by the observed drifter location after assimilation. From the covariance matrix projected on the data space, in this case the drifters' locations, we construct a set of correlation functions. There are as many correlation function as there are observations, i.e., two per drifter. These correlation functions simply describe the correlation between the state variables of the model and our observing system. The volume of influence of the observing system is then defined as being the volume for which at least one of the state variables has an absolute correlation greater than 0.3.

These volumes of influence can define a metric for the efficiency of assimilating different types of observation. A typical example of the volume of influence corresponding to the assimilation of one drifter is shown in Figure 3.

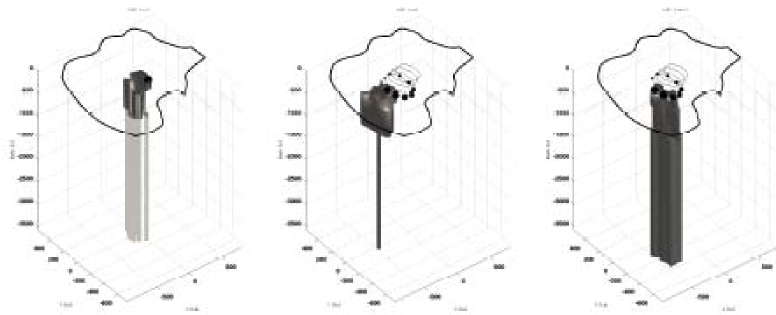

Figure 3: Volume of influence of one drifter. The black dot represents the location of the drifter. The gray surface is the boundary of the volume. From left to right, these represent LaDA2d, LaDA3d and EuDA, as above.

Significant progress has also been made on strategies to implement Bayesian approaches, including particle filtering and Langevin sampling. Results have been obtained from the implementation of a new approach to Lagrangian data assimilation using a Bayesian framework and Langevin-type sampling. The aim here is to develop techniques that deal effectively with the underlying nonlinearity in the system. We know that nonlinear effects are the cause of filter divergence, but they are also the reason that Lagrangian data are so information rich. It is therefore critical to develop and test methods that will effectively and efficiently exploit the nonlinear nature of the flow fields. The natural approach is to use Bayesian methods. These have the disadvantage of being only usable in low dimensions. However, the Lagrangian data live in a low-dimensional subspace and these methods therefore hold great promise.

We have implemented several methods, including the pure Langevin equation and Metropolis-Hastings algorithms, to sample the posterior distribution. Specifically, we have implemented these methods for the LaDA problem in linearized shallow water (LSW) equations using observations of the position of a drifter and augmenting the state space with the equations of the drifter. Since the flow model (LSW) is linear, we use two Fourier modes: the time-independent geostrophic mode that shows a cellular flow field, with hyperbolic fixed points, and a time-dependent Kelvin mode that perturbs the cellular flow field and leads to particle trajectories that cross the cell boundaries. Figure 4 shows one cell of the perturbed cellular flow field and a particularly striking result in which the pdf is highly non-Gaussian and yet reflected well by the Langevin sampling scheme.

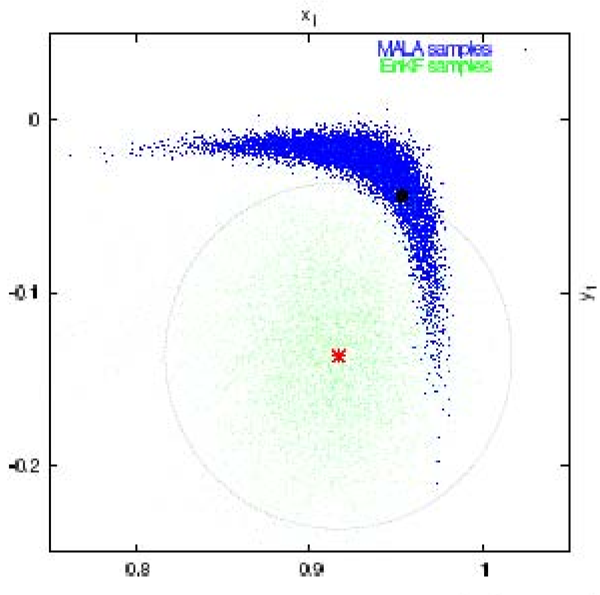

Figure 4: The cellular flow field and pdf's of the height field using Langevin (MALA) sampling and EnKF.

IMPACT/APPLICATION

Much data for the ocean is Lagrangian in nature and our techniques promise its effective use in predictive models. We are developing a refined scheme to incorporate this data into models of specific ocean regions. Our approach is adaptable to the incorporation of all data comng from moving instruments, including floats, AUVs etc.

As the scheme is developed to the point of efficacy in real time, its use in naval operations will have signficant application. Its impact will be further enhanced by the optimal deployment strategies being uncovered through the application of dynamical systems ideas. The development of LaDA in a realistic ocean model of GOM is being carried out on a model that is designed to offer a smooth transfer to operational naval models. Discussions have been initiated with personnel at NRL-Stennis to use some of these LaDA ideas in their operational models.

RELATED PROJECTS

ONR grant in Computational Analysis (Code 311)

PUBLICATIONS

Salman, H., K. Ide, and C.K.R.T. Jones, 2008: Using flow geometry for drifter deployment in Lagrangian data assimilation, Tellus A 60, 321-335

Vernieres, G., K.Ide and C.K.R.T. Jones, 2008: Lagrangian data assimilation, an application to the Gulf of Mexico, submitted

Apte, A., A. Stuart, J.Voss and C.K.R.T. Jones, 2008: Data Assimilation: Mathematical and Statistical Perspectives, International Journal for Numerical Methods in Fluids 56 (2008) 1033-1046

Apte, A., C.K.R.T. Jones and A.Stuart, 2008: A Bayesian approach to Lagrangian data assimilation, Tellus A 60 336-347

Spiller, E., A. Budiraja, K. Ide, and C.K.R.T. Jones, 2008: Modified particle filter methods for assimilating Lagrangian data into a point-vortex model, Physica D 237, 1317-1688

HONORS/AWARDS/PRIZES

Elected Advisory Board, SIAM Activity Group on Dynamical Systems;
Honorary Editor, Physica D;
Invited Review in Notices of the AMS: “Is Mathematics Misapplied to the Environment?” April 2008.